UNIVERSITY OF NAIROBI

FINAL YEAR PROJECT

SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE
AWARD OF THE BACHELOR OF SCIENCE DEGREE IN MECHANICAL AND
MANUFACTURING ENGINEERING

PROJECT CODE: GOR 01/2012

“THE EFFECT OF GALVANIC CORROSION ON THE FATIGUE CRACK GROWTH OF
MILD STEEL AND ALUMINIUM

AUTHORED BY:

KIPROTICH ROBERT F18/1883/2007

OUMA PATRIOT GUMBO F18/1884/2007

SUPERVISOR: PROF. G.O. RADING

DEPARTMENT OF MECHANICAL AND MANUFACTURING ENGINEERING
DECLARATION

We here declare that unless where indicated or quoted, the results, analysis and conclusions set out in this report are entirely our own efforts. To the best of our knowledge this work of research is entirely our own production and is not a previous submission in any institution of higher learning anywhere for award of a degree or any academic qualification.

Kiprotich Robert  
Patriot Gumbo

F18/1883/2007  
F18/1884/2007

Signature…………………………  
……………………………………..
DEDICATION

We dedicate this project to our beloved parents, siblings and friends for their sacrifice and support during our undergraduate studies.
ACKNOWLEDGEMENT

We are sincerely grateful to the following for their immense support through the challenges we faced in the duration of this project: Professor Rading for his guidance, advice, encouragement, support and constructive criticism, Mr. Githome, Mr. Macharia, Mr. Jackton, Mr. Aduol and other technical staff who were seriously involved in the preparation and actual performance of fatigue tests. To these kind hearted individuals we wish them good in all their endeavors. May God bless you.
Contents

DECLARATION ................................................................................................................... ii
DEDICATION ................................................................................................................... iii
ACKNOWLEDGEMENT ................................................................................................... iv
LIST FIGURE .................................................................................................................. viii
LIST OF TABLES ........................................................................................................... ix
Nomenclature ................................................................................................................ x
CHAPTER 1 .................................................................................................................... 1
BACKGROUND INFORMATION ...................................................................................... 1
1.1 Introduction ............................................................................................................... 1
  1.1.1 Galvanic Corrosion .......................................................................................... 2
  1.1.2 Fatigue Crack Growth ..................................................................................... 2
  1.1.3 Stress Corrosion .............................................................................................. 3
  1.1.4 Fatigue Stress Cycles ....................................................................................... 3
  1.1.5 Fracture ......................................................................................................... 4
  1.1.6 The S-N Curve ................................................................................................ 5
1.2 Steel ......................................................................................................................... 6
  1.2.1 Mild and low carbon steel ............................................................................. 6
1.3 Aluminium ............................................................................................................... 7
1.4 Problem Statement .................................................................................................. 7
LITERATURE REVIEW ...................................................................................................... 8
2.1 INTRODUCTION ....................................................................................................... 8
2.2 Fatigue ..................................................................................................................... 8
  2.2.1 Definition ......................................................................................................... 8
  2.2.2 Nature of fatigue ............................................................................................ 9
  2.2.3 Fatigue Parameters ......................................................................................... 10
  2.2.4 Fatigue Life/ Fatigue Strength ....................................................................... 10
  2.2.5 Fatigue of un-cracked components ................................................................ 10
    2.2.5.1 High-cycle fatigue ............................................................................... 10
    2.2.5.2 Low-cycle fatigue ............................................................................... 11
  2.2.6 Effect of mean stress on fatigue ..................................................................... 12
3.2.1 SERVICING, REPAIRS AND MAINTENANCE PROCEDURES ........................................... 37
3.2.2 TESTING PROCEDURE IN AIR .................................................................................. 38
3.2.3 TESTING PROCEDURE IN SODIUM CHLORIDE ENVIRONMENT .......................... 38
CHAPTER 4 .......................................................................................................................... 41
  4.1 Results ......................................................................................................................... 41
  4.2 Sample calculation ...................................................................................................... 41
  4.3 Determination of C and m ......................................................................................... 50
  4.4 DISCUSSION ............................................................................................................... 51
CHAPTER 5 .......................................................................................................................... 56
  5.1 CONCLUSIONS ........................................................................................................... 56
  5.2 RECOMMENDATIONS ............................................................................................... 56
6. BIBLIOGRAPHY ............................................................................................................... 57
7. APPENDIX: 1 ................................................................................................................... 59
LIST FIGURES

Figure 1: Static loading ........................................................................................................ 3
Figure 2: Random loading ..................................................................................................... 3
Figure 3: Constant amplitude loading ................................................................................... 4
Figure 4: Program Loading .................................................................................................... 4
Figure 5: Initiation-controlled high-cycle fatigue- The Basquin’s Law taken from Ashby [11] pp 148 .......................................................................................................................... 11
Figure 6: Initiation-controlled low-cycle fatigue- The Coffin Manson Law taken from Ashby [11] pp 149 .................................................................................................................................. 11
Figure 7: Effect of mean stress on SN curves taken from Meyers [13] pp. 719 ......................... 12
Figure 8: A graph showing the empirical relationship effect of mean stress taken from Meyers [13] pp. 720 ....................................................................................................................... 13
Figure 9: Schematic of crack propagation rate da/dN versus ΔK taken from Meyers [13] pp. 738 .................................................................................................................................. 14

Figure 10: Galvanic corrosion ................................................................................................ 22
Figure 11: Hydrogen blistering ............................................................................................... 26
Figure 12: Hydrogen embrittlement ....................................................................................... 28
Figure 13: Subcritical crack growth in fatigue [6] ................................................................ 31
Figure 14: Sub-critical crack growth in fatigue [6] ................................................................. 32
Figure 15: Sub-critical crack growth in fatigue [6] ................................................................. 32
Figure 16: Test rig assembly ................................................................................................. 35
Figure 17: Illustration of testing procedure in NaCl solution .................................................. 40
Figure 18: da/dN against ΔK in NaCl solution environment Mild Steel R=0.1 ....................... 42
Figure 19: da/dN against ΔK in air condition Mild Steel R=0.1 ........................................... 42
Figure 20: da/dN against ΔK Mild Steel R=0.1 .................................................................. 43
Figure 21: da/dN against ΔK in air condition Mild Steel R=0.5 ........................................... 44
Figure 22: da/dN against ΔK in NaCl condition Mild Steel R=0.5 ....................................... 44
Figure 23: da/dN against ΔK Mild Steel R=0.5 .................................................................. 45
Figure 24: da/dN against ΔK in air condition Al R=0.1 ....................................................... 46
Figure 25: da/dN against ΔK in NaCl solution environment Al R=0.1 ............................... 46
Figure 26: da/dN against ΔK Al R=0.1 ............................................................................. 47
Figure 27: da/dN against ΔK in air condition Al R=0.5 ....................................................... 48
Figure 28: da/dN against ΔK in NaCl solution environment Al R=0.5 ............................... 48
Figure 29: da/dN against ΔK Al R=0.5 (series 1= in air condition),(series 2= in NaCl condition) ................................................................................................................................. 49
Figure 30: log da/dN against log ΔK in air condition Mild Steel R=0.1 ............................. 50
Figure 31: Compact tension specimen (CT) ........................................................................... 59
LIST OF TABLES

Table 1: Theoretical yield shear strength [11] ................................................................. 18
Table 2: Calculated values of C and m ............................................................................. 51
Table 3: Mild Steel R=0.1 calculated values ΔK and da/dN ............................................ 60
Table 4: Mild Steel (R=0.5) calculated ΔK and da/dN ..................................................... 61
Table 5: Aluminium R=0.1 ............................................................................................. 62
Table 6: Aluminium R=0.5 ............................................................................................. 63
### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>- crack Length</td>
</tr>
<tr>
<td>(\Delta K)</td>
<td>- Stress Intensity</td>
</tr>
<tr>
<td>(W)</td>
<td>- Specimen Width</td>
</tr>
<tr>
<td>(B)</td>
<td>- Specimen Thickness</td>
</tr>
<tr>
<td>(R)</td>
<td>- Stress Ratio</td>
</tr>
<tr>
<td>(K)</td>
<td>- Crack tip Stress Intensity Factor</td>
</tr>
<tr>
<td>(N)</td>
<td>- Total Number of Cycles</td>
</tr>
<tr>
<td>(\Delta P)</td>
<td>- Applied Load</td>
</tr>
<tr>
<td>(\sigma_{\text{max}})</td>
<td>- maximum stress value</td>
</tr>
<tr>
<td>(\sigma_{\text{min}})</td>
<td>- minimum stress value</td>
</tr>
<tr>
<td>(\Delta \sigma)</td>
<td>- Cyclic Stress Range</td>
</tr>
<tr>
<td>(\sigma_a)</td>
<td>- Cyclic Stress Amplitude</td>
</tr>
<tr>
<td>(\sigma_m)</td>
<td>- Mean Stress</td>
</tr>
<tr>
<td>(\sigma_{\text{UTS}})</td>
<td>- Ultimate Tensile Strength</td>
</tr>
<tr>
<td>(\sigma_a)</td>
<td>- is the fatigue strength in terms of stress amplitude when (\sigma_m \neq 0)</td>
</tr>
<tr>
<td>(\sigma_o)</td>
<td>- is the fatigue strength in terms of stress amplitude when (\sigma_m = 0)</td>
</tr>
<tr>
<td>(\sigma_y)</td>
<td>- Yield stress</td>
</tr>
</tbody>
</table>
G - Energy Release Rate

E - Young’s Modulus

Ni, Nf - Number of Cycles to Crack Initiation, Number of Cycles to Failure

da/dN - Fatigue crack growth rate

A - Basquin’s constant

b - Basquin’s Exponent

mm - millimetre

N - Newton

kN - Kilonewtons

MPa - Megapascal

Hz - Hertz
ABSTRACT

In this experiment the effect of galvanic corrosion on the fatigue crack growth of mild steel and aluminium was studied. To study the fatigue crack growth, fracture mechanics approach was applied.

Compact tension specimens were cut according to ASTM E647 standards from aluminium and steel bars. The specimens were then thoroughly polished and the pre-cracked. The first set of tests was done in laboratory air condition. The rate of crack growth was observed using a travelling microscope. The instantaneous crack length and number of cycles was then recorded. The specimens were tested at stress ratios 0.1 and 0.5. The second set was done in a NaCl solution environment.

The graph of log da/dN against log ∆K was plotted and values of m and C determined. For mild steel R= 0.1 the value of m in air was found to be 3.389 and the value of C was found to be 1.1334 X 10^{-9} ; and the value of m in NaCl was found to be 3.5272 and the value of C was found to be 1.7968X10^{-9}.

It was found that in NaCl solution the fatigue crack growth rate is higher than in air environment. The value of C was found to increase with increase stress ratio (R) and also in NaCl solution environment. It was also found that an increase in stress ratio resulted in an increase of fatigue crack growth in air and NaCl environment. It was concluded that galvanic corrosion increases the rate of fatigue crack growth.
CHAPTER 1

BACKGROUND INFORMATION

1.1 Introduction

It has been recognized since nineteenth century that a metal subjected to a repetitive or fluctuating stress will fail at a stress lower than the required to cause fracture on a single application of load.

Fatigue has become progressively more prevalent as technology has developed a greater amount of equipment, such as automobiles, aircraft, compressors, pumps and turbines are subject to repeated loading and vibration, until today it is often stated fatigue accounts for at least 90% of all service failures due to mechanical causes.

The simultaneous action of cyclic loading and corrosion is known as corrosion fatigue. Corrosive attack without superimposed stress often produces pitting on the metal surface. The pits acts as notches and produce a reduction in fatigue strength. However, when corrosive attack occurs simultaneously with fatigue loading there is a very pronounced reduction in fatigue properties which is greater than the reduction produced by fatigue or corrosion independently. When corrosion and fatigue occurs simultaneously, the chemical attack greatly accelerates the rate at which fatigue crack propagates.

Corrosion fatigue study is of great importance because materials tend to fail under it so suddenly. The cracks that cause failure due to corrosion fatigue are not easily visible during inspection so they cause an impending threat.
1.1.1 Galvanic Corrosion

In Galvanic corrosion, a potential difference usually exists between two dissimilar metals when they are immersed in a corrosive or conductive solution.

If these metals are in contact, this potential difference produces electron flow between them, which in turn corrodes the material initiating cracks. The presence of a crack in a component of a machine or structure may weaken it and cause fracture.

1.1.2 Fatigue Crack Growth

The presence of cracks in a component of a machine or structure may weaken it so that it fails by fracturing into two or more pieces. Fracture mechanics always consists of the progressive growth of a crack and only the material that is instantaneously adjacent to the crack tip is the portion actually breaking at any particular moment.

Where cracks are difficult to avoid, a special methodology called fracture mechanics can be used to aid in selecting materials and designing components to minimize the possibility of fracture.

A fatigue failure is particularly insidious because it occurs without any obvious warning. Fatigue results in a brittle appearing fracture, with no gross deformation at failure. On a macroscopic scale the fracture surface is usually normal to the direction of the principle tensile stress.

A fatigue failure can usually be recognized from the appearance of the fracture surface, which shows a smooth region due to the rubbing action as the crack propagated through and a rough region, where the member has failed in a ductile manner when the cross-section was no longer able to carry the load. Frequently the progress of fracture is indicated by a series of rings or “beach marks”, progressing inward from the point of initiation of the failure.
A failure usually occurs at a point of stress concentration such as a sharp corner or notch or at a metallurgical stress concentration like an inclusion.

1.1.3 Stress Corrosion

Stress corrosion cracking refers to cracking caused by the simultaneous presence of tensile stress and corrosive medium. During stress-corrosion cracking, the metal or alloy is virtually unattacked over most of its surface, while fine cracks progress through it.

1.1.4 Fatigue Stress Cycles

At the outset it will be advantageous to define briefly the general types of fluctuating stresses which can cause fatigue. The figures serve to illustrate typical fatigue stress cycles.
1.1.5 Fracture

Fracture is the fragmentation or separation of a material, under the action of external forces, into two or more parts. It may occur as sudden breaking up of a material either as the end result or extensive plastic deformation, or as a result of fatigue in the part of the material. In actual
practice, the fracture of a material is a serious problem, and should always be avoided. It has be observed that most of the materials posses some of the other weakness due to the presence of submicroscopic defects known as cracks. These cracks act as the point of stress concentration. The actual fracture starts at these points, and propagate to cause complete fracture.

There are a number of potential sources of such cracks; moreover, surface scratches also serve as the notches for stress concentration. It has been found out that the maximum stress concentration occurs at the corners of the notch [15]. When the stress exceeds the cohesive strength in the region, the crack itself propagates. It has been observed that, usually, the magnitude of stress concentration at the cracks is much higher than that at normal cross-section.

Internal cracks or voids may also develop during the formation of the solids. In amorphous solids, the particles of dirt, dissolved gases also serve as the potential sources of defects which prove to be responsible for fracture.

1.1.6 The S-N Curve

The basic method of presenting Engineering fatigue data is by means of the S-N curve, a plot of stress, S, against the number of cycles to failure, N. A log scale almost always used for N.

The stress value is usually the nominal stress that is there is no adjustment for stress concentration. The S-N relationship is determined for a specified value of $\sigma_{\text{mean}}$, $R$ or $A$.

It will be noted that S-N curves are concerned chiefly with fatigue failure at a high number of cycles ($N10^5$ cycles)
1.2 Steel

It is an alloy of iron and carbon with carbon content up to a maximum of 1.4 wt%. The carbon occurs in form of iron carbide (Fe₃C), because of its ability to increase the hardness and strength of the steel. Other elements, e.g., silicon, sulphur, phosphorus and manganese are also present to a greater or lesser amount to impart certain desired properties to it. Most of the steel produced nowadays is plain carbon steel. Plain carbon steel is defined as steel which has its properties mainly due to its carbon content and does not contain more than 0.5 wt% of silicon and 1.5 wt% of manganese [15]. The plain carbon steels varying from 0.06 wt% carbon to 1.4 wt% carbon are divided into the following four types depending upon carbon content:

- Dead mild steel = 0.06-0.12 wt% carbon.
- Low carbon or mild steel = 0.10-0.25 wt% carbon
- Medium carbon steel = 0.25-0.55 wt% carbon
- High carbon steel = 0.55-1.4 wt%

1.2.1 Mild and low carbon steel

Mild steel is the most common form of steel because its price is relatively low while it provides material properties that are acceptable for many applications. Low carbon steel contains approximately 0.05–0.15% carbon and mild steel contains 0.16–0.29% carbon; making it malleable and ductile, but it cannot be hardened by heat treatment. Mild steel has a relatively low tensile strength, but it is cheap and malleable; surface hardness can be increased through carburizing.
It is often used when large quantities of steel are needed, for example as structural steel. The density of mild steel is approximately 7.85 g/cm$^3$ (7850 kg/m$^3$ or 0.284 lb/in$^3$) and the Young’s modulus is 210 GPa (30,000,000 psi)

1.3 Aluminium

It is a white metal produced by electrical process from the oxide (alumina), which is prepared from clayey mineral called bauxite. It is a light weight metal having specific gravity 2.7 and melting point of 660°C.

In its pure state, the metal would be weak and soft for most purposes. But when mixed with small amounts of other alloys, it becomes hard and rigid. So, it may be blanked, formed, drawn turned, cast, forged and die cast. Its good electrical conductivity is an important property and is widely used for overhead cables. The high resistance to corrosion and its non toxicity makes it a useful metal for cooking utensils under ordinary conditions. It is extensively used in aircraft and automobile components where saving of weight are an advantage.

1.4 Problem Statement

Since the nature and understanding of corrosion fatigue is still not clearly understood (shown by the accidents caused by failure due to corrosion fatigue like Aloha flight accident) this project tries to analyze and bring more understanding of corrosion fatigue.

1.5 Objectives

The aim of the project is to study the effect of galvanic corrosion on fatigue crack growth of mild steel and aluminium.
CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Quantitative understanding of corrosion fatigue has been hampered by the complexity of the problem. This understanding is fundamental to service life prediction, fracture control, and the development of fatigue resistant alloys. Understanding of this phenomenon have been hampered by the complexity of the problem with difficulty in separating the effects associated with crack initiation from those associated with crack growth, and the influence of the external chemical environments on both the initiation and growth process.

In terms of understanding this problem it has been divided into two areas:

1. Mechanisms for fatigue crack growth
2. Environment enhancement of fatigue crack growth

There is need in development of a fundamental approach involving fracture mechanics, material science, and surface chemistry.

2.2 Fatigue

2.2.1 Definition

The process of progressive localized permanent structural damage occurring in a material subjected to conditions that produce fluctuating stress and strain at some points or points and that may culminate in cracks or complete fracture after sufficient number of fluctuations [13].
Fatigue can also be defined as a progressive, localized and permanent structural change that occurs in a material subjected to repeated or fluctuating strains at normal stress that have maximum values less than (and more often much less than) the static yield strength of the material.

2.2.2 Nature of fatigue

Fatigue damage is caused by simultaneous action of cyclic stress, tensile stress and plastic strain. If any one of this is not present a fatigue crack will not initiate and propagate.

Plastic strain initiates the cracks; the tensile stress promotes crack growth (propagation). Moreover, “although compressive stress will not cause fatigue, compressive stress may result in local tensile stresses. Microscopic plastic strains also can be present at low levels of stress where the strains might otherwise appear totally elastic.”

Fatigue can be stress based, strain based and fracture mechanics based [14]. The stress life approach which is the oldest way of treating cyclic fatigue data is useful when the stress and strains are mostly elastic, the main drawback of this approach being that, using this approach it is difficult to distinguish between initiation and propagation phase of fatigue life.

The strain life approach is useful when there is significant amount of plastic strain. Fatigue life is typically quite short under these conditions.

In fracture mechanics approach, the cyclic stress intensity factor, $K$, is used as crack driver. Stress intensity factor characterizes the severity of crack situation as affected by crack size, stress and geometry. In defining $K$, the material is assumed to behave in a linear-elastic manner. It allows the estimate of the life spent in propagating a crack from initial size to a larger size or the critical, $K_c$ (fracture toughness); size corresponding to failure.
2.2.3 Fatigue Parameters

Cyclic stress range \[ \Delta \sigma = \sigma_{max} - \sigma_{min} \]  \hspace{1cm} (2.1)

Cyclic stress amplitude \[ \sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2} \]  \hspace{1cm} (2.2)

Mean stress \[ \sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} \]  \hspace{1cm} (2.3)

Stress ratio \[ R = \frac{\sigma_{min}}{\sigma_{max}} \]  \hspace{1cm} (2.4)

2.2.4 Fatigue Life/ Fatigue Strength

Fatigue life refers to the capacity of a material to resist conditions of cyclic loading. However, in presence of a measurable plastic deformation materials respond differently to strain cycling than to stress cycling.

2.2.5 Fatigue of un-cracked components

2.2.5.1 High-cycle fatigue

In this case the entire range of stresses applied falls below the yield stress. The material is thus more likely to survive long without failure. It’s found to fit empirically the relationship

\[ \Delta \sigma N_f^a = C_1 \text{ Basquin’s Law} \] \hspace{1cm} (2.5)

Where \( a \) is a constant between 1/8 and 1/5 for most materials, and \( C_1 \) is a constant
2.2.5.2 Low-cycle fatigue

In this case the stresses applied are above the yield stress of the material. It thus only a short time under the given cyclic loading before plastic deformation leads to crack initiation and subsequent failure.

\[ \Delta \varepsilon_{pl} N_f^b = C_2 \text{ Coffin – Manson Law} \]  

(2.6)

Where \( C_2 \) and \( b \) are constants \( 0.5 < b < 0.6 \)
2.2.6 Effect of mean stress on fatigue

For a given stress amplitude, as mean stress increase, the fatigue life decreases.

![Graph showing SN curves with different mean stresses](image)

**Figure 7: Effect of mean stress on SN curves taken from Meyers [13] pp. 719**

Various empirical expressions have been proposed that take into account the effect of mean stress on fatigue life.

Goodman relationship which assumes a linear effect of mean stress between $\sigma_m = 0$ and $\sigma_{UTS}$

$$\sigma_a = \sigma_o \left(1 - \left(\frac{\sigma_m}{\sigma_{UTS}}\right)\right) \quad (2.7)$$

Gerber relationship which assumes a parabolic effect of mean stress between $\sigma_m = 0$ and $\sigma_{UTS}$

$$\sigma_a = \sigma_o \left(1 - \left(\frac{\sigma_m}{\sigma_{UTS}}\right)^2\right) \quad (2.8)$$

Soderberg’s relationship which assumes linear effect of mean stress between $\sigma_m = 0$ and $\sigma_y$

$$\sigma_a = \sigma_o \left(1 - \left(\frac{\sigma_m}{\sigma_y}\right)\right) \quad (2.9)$$
2.2.7 Fatigue crack growth test.

The integrity of components which may contain cracks depends on the crack propagation phase. Since the study of this growth involves cracks, it is feasible that fracture mechanics may be used for this study [13].

Paris studied this and concluded that the rate at which the crack growth/loading cycle could be related to range of stress intensity. This in turn depends on the maximum stress and the minimum stress. On plotting $\frac{da}{dN}$ Vs $\Delta K$, the graph obtained by Paris has a sigmoidal shape.
Figure 9: Schematic of crack propagation rate $\frac{da}{dN}$ versus $\Delta K$ taken from Meyers [13] pp. 738

Regime 1

At low values of $\Delta K$, crack propagation is extremely slow. Conceivably there is a threshold stress intensity factor below which there is no fatigue crack growth. The fatigue threshold decreases with an increasing stress ratio $R$. The fatigue threshold also depends on the frequency of the loading and the environmental conditions. Region one is also referred to as threshold regime. The threshold value may be useful when a component is subjected to low stress levels.

Regime II

In the mid-region of stress intensities, the curve of $\log \frac{da}{dN}$ versus $\log (\Delta K)$ is essentially linear. Most structures operate in this region. Most of the current applications of linear elastic fracture mechanics concepts used to describe fatigue crack behavior are associated with this region.

Region II is characterized by linear relationship between $\log \frac{da}{dN}$ versus $\log (\Delta K)$
\[
\log_{10} \frac{da}{dN} = \log_{10} C + m \log_{10} (\Delta K)
\]

\[
= \log_{10} C + m \log_{10} (\Delta K)^m
\]

\[
= \log_{10} C (\Delta K)^m
\]

Therefore \(\frac{da}{dN} = C (\Delta K)^m\) \hspace{1cm} (2.10)

Where \(C\) is a constant and \(m\) is the slope in log-log plot shown above. Regime II there is relatively little micro-structural influence, of stress ratio effect or even environmental effects on fatigue crack growth behavior and hence on the constants \(C\) and \(m\).

**Regime III**

At high stress intensities, crack growth rates are extremely high and little fatigue life is involved. Region III is characterized by rapid, unstable crack growth. The crack growth rate accelerates as the maximum stress intensity factor approaches the fracture toughness of the material.

The stress levels in this region are very high so that crack extension due to the static modes of failure such as cleavage and micro-void coalescence is superposed onto the mechanisms of cyclic subcritical crack extension.

Since static fracture modes are sensitive to microstructure and stress state, the growth rates in this region are sensitive to microstructure, stress ratio and specimen thickness.

However, because \(\frac{da}{dN}\) in this region is very high, it is not sensitive to the environment and the frequency. This regime is also called static mode regime.
2.2.8 Fatigue crack closure

Under certain circumstances, surface of a fatigue of a crack can contact each other and the crack will close even when the far field stress is still tensile. This crack doesn’t reopen until a sufficiently high tensile stress is reached in the next loading cycle. This phenomenon crack-closure may occur as a result of crack-tip plasticity.

As applied stress on the material is increased, a plastic zone develops at the crack tip, while the material surrounding is still elastic. The explanation is that the plastically deformed zone caused the crack to close before zero stress is reached. However, for fatigue crack growth to occur, the crack must be fully open, thus pre-mature contact between the crack surfaces.

Among the various phenomenon hold responsible for crack closure are crack surface roughness, asperities in the crack wake from oxides or corrosion products, viscous fluid and phase transformation ahead of the crack tip.

The oxide induced crack closure is possible in a material that forms oxide film on the surface easily. When such a material is subjected to cyclic stress near the threshold regime at low load ratios and in moist environment, corrosion products of thickness comparable to crack tip opening displacements can build up at and near the tip.

This phenomenon is unlikely to occur at high frequencies. Crack closure cause an increase in stiffness and a decrease in compliance. High values of stress ratio result in less crack closure.
2.3 Fracture Mechanics

Fracture mechanics is the field of mechanics concerned with the study of the propagation of cracks in materials. It uses methods of analytical solid mechanics to calculate the driving force on a crack and those of experimental solid mechanics to characterize the material's resistance to fracture.

In modern materials science, fracture mechanics is an important tool in improving the mechanical performance of materials and components. It applies the theories of stress and strain, in particular the theories of elasticity and plasticity, to the microscopic crystallographic defects found in real materials in order to predict the macroscopic mechanical failure of bodies.

Fracture mechanics gained its prominence during the post world war II period. When design in terms of strength level alone was shown to be inadequate. The strength of a material as measured in tests was regarded as an intrinsic characteristic and all individual sample of a population of a given material was expected to always have the same properties. Indeed, materials are assemblage of atoms; it stands to reason that their strength must depend on the bond strengths between those atoms.

It was found, however, that the expected strengths based on bond strength calculations were far in excess to those measured in practice. This is because of the effects of irregularities in the arrangement of atoms in a material, for example, dislocations in metals and stress concentrations in structures, caused by flow in a material. These were found to be responsible for causing failure at stresses far lower than expected.
The theoretical shear strength of a perfect crystal was calculated by Frenkel [11] considering the displacement of one row of atoms over another, in a rigid cooperative motion from a position of perfect registry to the next, under a shear force. He came up with the formula for calculating theoretical strength of the crystal and found out that the theoretical shear strength is about a sixth of the shear modulus as shown in the table below.

**Table 1: Theoretical yield shear strength [11]**

<table>
<thead>
<tr>
<th>Material</th>
<th>G/2π (GPa)</th>
<th>σ_y (MPa)</th>
<th>τ_m/τ_exp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag</td>
<td>12.6</td>
<td>0.37</td>
<td>~3×10^4</td>
</tr>
<tr>
<td>Al</td>
<td>11.3</td>
<td>0.78</td>
<td>~1×10^4</td>
</tr>
<tr>
<td>Cu</td>
<td>19.6</td>
<td>0.45</td>
<td>~4×10^4</td>
</tr>
<tr>
<td>Ni</td>
<td>32</td>
<td>3.2~7.4</td>
<td>~1×10^4</td>
</tr>
<tr>
<td>Mg</td>
<td>7</td>
<td>0.39</td>
<td>~2×10^4</td>
</tr>
<tr>
<td>Ti</td>
<td>16.9</td>
<td>13.7</td>
<td>~1×10^3</td>
</tr>
</tbody>
</table>

\[ \tau_y = \frac{G}{2\pi} \quad \text{(2.11)} \]

This shows very clearly that the actual stresses measured fall short of theoretical. This is because most practical materials contain flaws. In brittle materials the type of flaw in consideration is cracks, while with metals its dislocation.
2.4 CORROSION

Corrosion is the destruction or deterioration of a material because of reaction with its environment. Corrosion not only occurs in metals as perceived by many, but also in non-metals; for example, deterioration of paint and rubber by sunlight or chemicals, fluxing of the lining of a steelmaking furnace and attack of a solid metal by another molten metal [8].

For corrosion to occur the metal atom must undergo transformation from its pure un-reactive state to an ionic state, which is an oxidation process. Oxidation is a reaction causing a decrease in electronegative charge of an atom whereas reduction is the increase in electronegative charge, e.g. an oxygen molecule changing into two oxygen anions.

If a metal is in contact with water, there is a tendency for ions to enter into water, creating a solution of metal ions. This tendency originates in the desire for atoms to adopt a noble gas electronic configuration. While the metallic state is able to lower the energy of the metals atom significantly through the delocalized electronic cloud, it is generally preferable for the atoms to lose their valence entirely becoming free ions. The electrons remain in the metal, rendering it negatively charged. However, as soon as separation occurs, an electrical potential is set up tending to reverse the separation. An electrical double layer is set up comprising negative charges on the metal and metals ions in the solution congregating adjacent to it due to cumblic attraction. A certain concentration a metal ion in the solution, this tendency to dissolve is equally and oppositely matched by the tendency to redeposit; this state is referred to as equilibrium.
2.4.1 Passivity

This refers to the loss of chemical reactivity experienced by certain metals and alloys under particular environmental conditions. Certain metals and alloys become essentially inert and act as if they were noble metals such as platinum and gold. Fortunately, from engineering standpoint, the metals most susceptible to this kind of behavior are the common engineering and structural materials, including iron, nickel, silicon, chromium, titanium, and alloys containing these metals. Also under limited conditions other metals such as zinc, cadmium, tin, uranium, and thorium have also been observed to exhibit passivity effects.

The behavior of these metals or alloys can be conveniently divided into three regions: active, passive, and trans-passive. In the active region the behavior of this material is identical to that of a normal metal; slight increase in the oxidizing power of the solution cause a corresponding rapid increase in corrosion rate. If more oxidizing agent is added, the corrosion rate shows a sudden decrease. This corresponds to the beginning of the passive region. Further increases in oxidizing agents produce little, if any, change in corrosion rate of the material. Finally, at very high concentrations of oxidizers or in presence of very powerful oxidizers the corrosion rate again increases with increasing oxidizing power. This region is termed as the trans-passive region.
2.4.2 Forms of corrosion

Some forms of corrosion are:

2.4.2.1 Galvanic Corrosion

It is form of corrosion in which dissimilar metals corrode when placed in corrosive environment or solution due to the potential difference between the metals. If the metals are put in contact (or otherwise electrically connected), the potential difference produce electrons flow between them. Corrosion of the less corrosion resistant metal is usually increased and the attack of the more resistant metal is decreased as compared with these metals when they are not in contact. The less resistant metal becomes the anode and the more resistant metal becomes the cathode. The metal that acts as cathode corrodes less or not at all in this type of couple. The potential differences between the metals under reversible or non-corroding condition form the basis of predicting corrosion tendencies of the metals. If the potential between metals exposed to solutions containing approximately one gram atomic weight of respective ions are precisely measured at constant temperature. An electromotive series is developed. In this series, it is not possible to establish a reversible potential for alloys containing two or more reactive components. In actual corrosion problems, galvanic coupling between metals in equilibrium with their ions rarely occurs. Most of the galvanic corrosion effects result from the electrical connection of two corroding metals. But since most materials are alloys galvanic couples usually include one or two metallic alloys. Under such conditions the galvanic series is more accurate in prediction of corrosion tendencies than the electromotive series. In general, the position of a metal and an
alloy in galvanic series, agree closely with their constituent elements in the electromotive series.

In most practical applications there is little danger of galvanic corrosion of metals close to each other in galvanic series are coupled become there is little potential difference generated. The rate of electrochemical in galvanic corrosion polarization plays a major role. Reaction is limited by various physical and chemical factors. Hence an electrochemical reaction is said to be polarized or retarded by these environmental factors.

Figure 10: Galvanic corrosion

Factors affecting galvanic corrosion

Environmental effects

The nature and the aggressiveness of the environment determine to a large extent the degree of two-metal corrosion. Usually the metal with lesser resistance to the given environment becomes the anodic member of the couple sometimes the potential reverse for a given couple in different environments.
Galvanic corrosion also occurs in atmosphere. The severity depends largely on the type and the amount of moisture present. For example is great near seashore great near the sea shore than in a dry rural area atmosphere. Condensate near a sea shore contains salt and therefore in more conductive and a better electrolyte than condensate in an inland location, even under equal humidity and temperature conditions. Galvanic corrosion does not occur when the metals are completely dry since there is no electrolyte to carry the current between the two electrode areas.

**Distance effects**

Accelerated corrosion due to galvanic effects is usually greatest near the junction, with attack decreasing with increasing distance from that point.

**Area effects**

These are the effects that results from the ratio of cathodic to anodic areas. An unfavorable area ratio consists of a large cathode to a small anode. For a given current flow in the cell, the current density is greater for a small electrode than for a large one. The greater the current density at an anodic area the greater corrosion rate. Corrosion of the anodic area may be 10 to 100 times greater than if the anodic and cathodic areas were equal in size.

**Prevention of galvanic corrosion**

1. Electrically insulate the two metals from each other for example plastic to separate still water
2. Another way is to keep the metal dry or shielded from ionic compounds by painting or encasing the protected metal in plastic or epoxy and allowing them dry
3. Coating the materials or if not possible to coat both. The coating shall be applied only on nobler material.

4. Choosing of metals that have similar potentials

5. Electroplating

6. Cathodic protection

2.4.2.2 Crevice Corrosion
This type of corrosion is associated with small volumes of stagnant solution caused by holes gasket surfaces, lap joints, surface deposits and crevices under bolt and river heads. Localized corrosion frequently occurs within crevices and other shielded areas on metal surfaces exposed to corrosives.

2.4.2.3 Uniform Attack
It is normally characterized by a chemical or electrochemical reaction that proceeds uniformly over the entire exposed surface or over the large area. The metal becomes thinner and finally fails. For example a sheet roof will show essentially the same degree of rusting over its entire outside surface.

2.4.2.4 Pitting Corrosion
Pitting is a form of extremely localized attack that results in holes in the metal. It is one of the most destructive and insidious forms of corrosion. It causes equipment to fail because of perforations with only a small percent weight loss of the entire structure. It is often difficult to detect pits because of their small size and because pits are often covered with corrosion products.
2.4.2.5 Inter-granular corrosion

It is a localized attack at and adjacent to grain boundaries, with relatively little corrosion of the grains. This leads to grains of the alloy falling out and the material losing out its strength. Grain boundary effects are of little or no consequence or of use of the metal. If a metal corrodes, uniform attack results since grain boundaries are usually only slightly more reactive than the matrix.

However, under certain conditions grain interfaces are very reactive and inter-granular corrosion can result. This corrosion can be caused by impurities at the grain boundaries, enrichment of one of the alloying elements or depletion of one of this element in the grain boundary areas.

2.4.2.6 Erosion corrosion

This is the acceleration or increase in the rate of deterioration or attack on a metal because of relative movement between a corrosive fluid and the metal surface. Metal is removed from the surface as dissolved ions, or it forms solid corrosion products that are mechanically swept from the metal surface.

2.4.3 Hydrogen damage

Hydrogen damage is the general term which refers to mechanical damage caused by the presence of, or interaction with, hydrogen.
2.4.3.1 Hydrogen Blistering

This is penetration of hydrogen into a metal which results in a local deformation and, in extreme cases, complete destruction of a material wall. A schematic illustration of mechanism of hydrogen blistering is shown below. The interior contains an acid electrolyte, and the exterior is exposed to the atmosphere. Hydrogen evolution occurs on the inner surface as a result of corrosion reaction or cathodic protection. At any time there is a fixed concentration of hydrogen atoms on the metal surface, and some of these diffuse on to the metal rather than combining into molecules, as shown.

![Formation of blisters under the metal surface.](image)

**Figure 11: Hydrogen blistering**

Much of the hydrogen diffuses through the steel and combines to form hydrogen molecules on the exterior surface. If hydrogen atoms diffuse into a void, a common defect in rimmed steels, they combine into molecular hydrogen. Since molecular hydrogen cannot diffuse, the concentration and pressure of hydrogen gas within the void increases. The equilibrium pressure
of molecular hydrogen in contact with atomic hydrogen is several hundred thousand atmospheres which is sufficient to rupture any known engineering material.

Hydrogen blistering is most prevalent in the petroleum industry. It occurs in the storage tanks and in refining processes. One method for control it is to add an inhibitor, such as the polyulphide ion.

2.4.3.2 Hydrogen Embrittlement

This is caused by penetration of atomic hydrogen into the metal structure. For titanium and other strong hydride forming metals, dissolved hydrogen reacts to form brittle hydride compounds. In other materials such as iron and steel, the interaction between dissolved hydrogen atoms and metal is not completely known.

There are indications that a large fraction of all the environmentally activated cracking of ferretic and martensitic iron-base alloys and titanium-base alloys is due in some way to the interaction of the advancing crack with hydrogen. At higher strength levels, steel is more susceptible to cracking and that higher stresses cause cracking to occur more rapidly.

These trends are in fact general for most alloys subject to hydrogen embrittlement i.e the alloys that are most susceptible to cracking in their highest strength level. The tendency for embrittlement is increased with hydrogen concentration in the metal. Most of the mechanisms that have been proposed for hydrogen embrittlement are based on slip interference by dissolved
hydrogen. This slip interference may be due to the accumulation of hydrogen near dislocation sites or micro-voids, but the precise mechanism is still in doubt.

Hydrogen embrittlement is distinguished from stress-corrosion by cracking generally by the interactions with applied currents. Cases where the applied current makes the specimen more anodic and accelerates cracking are considered to be stress-corrosion cracking, with anodic dissolution process contributing to the progress of cracking. On the other hand, case where cracking is accentuated by current in the opposite direction, which accelerates the hydrogen evolution reaction, are considered to be hydrogen embrittlement.

![Hydrogen embrittlement](image)

**Figure 12: Hydrogen embrittlement**

**2.4.3.3 Decarburization and Hydrogen attack**

This is the removal of carbon from steel, is often produced by moist hydrogen at high temperatures. At elevated temperatures, hydrogen can influence the mechanical properties of metal in a variety of ways. Since most high-temperature gas streams are mixtures of gases, it necessary to consider the effect of hydrogen in presence of other gases. One effect of hydrogen at high temperatures is that of decarburization, or removal of carbon from an alloy. If the alloy is
strengthen by interstitial carbon or by carbide precipitates, decarburization results in a reduction of tensile strength and an increase in ductility and creep rate. Thus, after long-term exposure to hydrogen at elevated temperatures, steel tend to lose their strength. The reverse is frequently encountered in petroleum-refining operations.

For low-alloy steel, carburization is usually less detrimental than decarburization, although addition of carbon to an alloy tends to reduce its ductility and remove certain solid-solution elements through carbide precipitation. Also, hydrogen penetration into a metal can cause scale spallation and metal fracture or rapture resulting from the formation of molecular hydrogen in internal voids upon cooling.

There are two types of decarburization:

2.5 CORROSION FATIGUE

Corrosion fatigue is a mechanical degradation of a material under the joint action of corrosion and cyclic loading. Corrosion fatigue seems to be most prevalent in mediums that produce pitting attack.

Fatigue resistance is reduced by corrosion because the pits act as stress raisers and initiate cracks. It is most likely that that corrosion is most intense at the crack tip.

2.5.1 Effect of corrosion on S-N curve diagram

Corrosion lowers the fatigue strength; it causes accelerated initiation at higher stresses and elimination of fatigue limit.
2.5.2 Crack propagation studies in corrosion fatigue

In normal fatigue testing of smooth specimens about 90% of life is spent in crack nucleation and only 10% of the remaining in crack propagation. However in corrosion fatigue, crack nucleation is facilitated by corrosion and typically 10% of life is sufficient for this stage. The rest of 90% of life is spent in crack propagation. Fracture mechanics uses pre-cracked specimens and efficiently measures crack propagation behavior. Hence considerable emphasis is being given to crack propagation rate using fracture mechanics to study corrosion fatigue.

Crack propagation under corrosion fatigue may be classified into:

1. True corrosion fatigue
2. Stress corrosion fatigue
3. A combination of true and stress corrosion fatigue

2.5.2.1 True corrosion fatigue

In true corrosion fatigue, the graph is enhanced by corrosion in all 3 regions. The curve shifted to the left to lower stress intensity factor range. The threshold is lower and crack growth velocities higher at all stress intensity factor.
2.5.2.2 Stress corrosion fatigue

In materials where the maximum applied stress intensity factor exceeds the stress corrosion cracking threshold value, stress corrosion will add to the crack growth rate.

In corrosive environment the crack grows due to cyclic loading at lower stress intensity factors but above threshold stress intensity factor additional cracking happens due to stress corrosion cracking.

Figure 13: Subcritical crack growth in fatigue [6].
Figure 14: Sub-critical crack growth in fatigue [6]

Combined true and stress corrosion fatigue

Figure 15: Sub-critical crack growth in fatigue [6]
2.5.3 PREVENTION OF CORROSION FATIGUE

- Increasing the tensile strength of a metal or alloy improves ordinary fatigue but detrimental to corrosion fatigue. As corrosion initiate crack grows faster in higher tensile stress.
- Can be prevented by reducing stress on the component
- Can be reduced by altering design, by stress relieving heat treatments
- By short-peening the surface to induce compressive stresses
- Can also be improved by coating with electrodeposited zinc, chromium, Nickel, Copper, Nitride coatings
- Corrosion inhibitors also reduce corrosion fatigue
CHAPTER 3

3.1 EXPERIMENTAL DEVICES AND DATA ANALYSIS TECHNIQUES

3.1.1 EXPERIMENTAL DEVICES

THE TEST RIG

This was the machine that was used to test fatigue growth. The drawings of the test rig that was designed and constructed by Prof. G.O Rading to test for FCG at 24Hz are given in the figure below. The rig was coupled to a motor running at 1498rpm. The rotary motion was then converted to oscillatory motion by an eccentricity to the force transmitting lever.

The up and down movement of the piston was preset by setting the angle on the wheel, in this case to four degrees. A universal joint was provided to reduce the horizontal component of motion of the piston so that only the axial forces were transmitted to the lower clevis. A strain gauge indicator on quarter bridge connection was used to measure the strains. A preload was applied by tightening the lock nut until the desired value of strain corresponding to the minimum load from the calibration graph was attained. This load was calculated using ASTM E standard specification for CT specimens (ASTM E399, by Scrawley) from the dimensions of the specimen. We machined washers to ensure that the specimens were well gripped and hence only the cyclic load was extending the crack.
3.1.2 MEASUREMENT OF CRACK LENGTH

3.1.2.1 Microscopic Observation

This was the method used to measure crack length and it involves visual observation of the crack using a travelling microscope. Crack length could be measured to 0.1mm using an X10 magnification microscope mounted on a travelling base. Restrictions here include the fact that only surface cracks could be observed.

3.1.3 FATIGUE SPECIMEN PREPARATION

The specimens used in the fatigue crack growth analysis are of the specification according to ASTM E647 standard compact tension type Fig 31. Metal was cut from aluminum and steel flat bars. The shaping machine was then employed to machine the pieces to the desired dimensions.
with subsequent drilling process as per the ASTM standards. A 5mm thick cutter on and horizontal milling machine was used to slot. A combination of a set of triangular files was used to cut a 30 degrees notch. A junior hacksaw blade with its teeth sharpened was used to initiate a sharp crack at the tip of the notch. Crack tip monitoring was improved by polishing the expected crack path using successively finer grades of abrasive paper from grades 220, 320, 400, to 600 of silicon carbide papers after using emery cloths of different grades to the finest. Eventually the specimen was well polished.

### 3.1.4 DATA ANALYSIS TECHNIQUES

**Determination of Stress-Intensity Factor Range, ΔK**

The stress-intensity range corresponding to a given crack growth rate was computed using the following expression as outlined in ASTM E561;

\[
\Delta K = \frac{\Delta P(2+\alpha)}{B\sqrt{W(1-\alpha)^{1.5}}} f(\alpha)
\]

Where;

\[
f(\alpha) = 0.866 + 4.64\alpha - 13.33\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4
\]

and; \( \alpha = \frac{a}{w} \)

\( a \) = crack length

\( W \) = effective width of the specimen

\( B \) = thickness of specimen

\( \Delta P \) = load range
3.1.5 Determination of Crack Growth Rate

Fatigue crack growth rate usually is determined from crack length measurements versus the number of cycles elapsed.

The recommended data reduction techniques in ASTM 647 are:

- Graphical method
- Secant method
- Incremental polynomial method

3.1.5.1 Graphical method

This is the method that was used to analyze the results. Here the best fit is obtained for the data of crack length ‘a’ versus N, cycles. The slope of this curve is determined at each given set of data points \((a_i, N_j)\). The accuracy of this method depends on the accuracy and precision in determining the best fit curve and most accurate slope at each data point.

The advantage of this method is that the calculated growth rate over several data points. Nevertheless, errors may arise from the subjective choice of the best fitting curve and the best slope.

3.2 EXPERIMENTAL PROCEDURE

3.2.1 SERVICING, REPAIRS AND MAINTENANCE PROCEDURES

The test rig was first totally dismantled so that the angle set on the wheel plate could be adjusted to four degrees. Washers were then machined so that the specimens would be tight at the jaws and be subjected to the cyclic load and not vibrations. The lubrication oil was changed. A new bearing was bought and press-fitted onto the shaft. Then the rig was assembled and aligned to
run smoothly. The test rig was then run for about two hours without a load. A specimen was then mounted between the jaws of the test rig. The travelling microscope was placed near the set up.

3.2.2 TESTING PROCEDURE IN AIR

A bulb was set to provide light to the set up. A well polished and pre-cracked specimen was set between the jaws of the test rig tightly by the use of spacers and clevis pins. A load was set on the load cell by the use of a spanner to tighten the overhead nut. This was followed by tightening the lock nut so that the specimen was only subjected to constant load amplitude. The travelling microscope was put in position making sure that the initial crack length was observable through the eye piece. The stop watch was set to read zero. The specimen was then subjected to repeated stress cycles by running the motor. The readings of the crack length and stop watch were taken correspondingly at different time intervals. A constant stress ratio $R$ was maintained throughout the procedure for a given specimen. This was progressively continued until the specimen was almost about to fail in an unstable manner. This procedure was repeated for the entire range of specimen tested for fatigue crack growth characteristics. Results obtained are as tabulated herein and analysis as documented.

3.2.3 TESTING PROCEDURE IN SODIUM CHLORIDE ENVIRONMENT

The surface was cleaned to remove dirt, grease, oil, and oxides. The specimen was immersed in full test condition (inside sodium chloride solution) for 24 hours prior to pre-cracking. Pre-cracking was done in ambient air as was done in the procedure above- test in air. However final 1mm increment was conducted in aqueous environment under full test solution.

The corrodent (3.5% NaCl) was drip fed from a pipette on the crack surface as shown below and the crack length monitored using a travelling microscope.
The specimen was visually examined periodically during the course of the experiment for evidence of corrosive attack. Corrosion products accumulation was removed from time to time from the crack tip for visibility.
Figure 17: Illustration of testing procedure in NaCl solution
CHAPTER 4

4.1 Results

Data for crack length, a mm and number of cycles, N were recorded and this were used to calculate $da/dN$ and $\Delta K$ as shown below. The values of $da/dN$ and $\Delta K$ are given in appendix 2.

4.2 Sample calculation

$$\Delta K = \frac{\Delta P (2+\alpha)}{B \sqrt{W(1-\alpha)^{1.5}}} \left(0.866 - 4.64\alpha - 13.33\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4\right)$$  \hspace{1cm} (4.1)

Where;

$$\alpha = \frac{a}{W} = \frac{19.2}{80} = 0.24$$  \hspace{1cm} (4.2)

$a$ = crack length $= 19.2$mm

$W$ = effective width of the specimen $= 80$mm

$B$ = thickness of specimen $= 5$mm

$\Delta P$ = load range $= 3337.306$N

$\Delta K = 11.42582$
Figure 18: $\frac{da}{dN}$ against $\Delta K$ in NaCl solution environment Mild Steel $R=0.1$

Figure 19: $\frac{da}{dN}$ against $\Delta K$ in air condition Mild Steel $R=0.1$
Figure 20: da/dN against ∆K Mild Steel R=0.1
Figure 21: $da/dN$ against $\Delta K$ in air condition Mild Steel $R=0.5$

Figure 22: $da/dN$ against $\Delta K$ in NaCl condition Mild Steel $R=0.5$
Figure 23: da/dN against ΔK Mild Steel R=0.5
Figure 24: $\frac{da}{dN}$ against $\Delta K$ in air condition Al $R=0.1$

Figure 25: $\frac{da}{dN}$ against $\Delta K$ in NaCl solution environment Al $R=0.1$
Figure 26: da/dN against ∆K Al R=0.1
Figure 27: $\frac{da}{dN}$ against $\Delta K$ in air condition Al R=0.5

Figure 28: $\frac{da}{dN}$ against $\Delta K$ in NaCl solution environment Al R=0.5
Figure 29: $da/dN$ against $\Delta K$ Al $R=0.5$ (series 1= in air condition), (series 2= in NaCl condition)
4.3 Determination of C and m

The Paris equation is expressed as:

\[
\frac{da}{dN} = C(\Delta K)^m
\]  

(4.3)

This can be expressed as:

\[
\log_{10}\left(\frac{da}{dN}\right) = \log_{10}C + m \log_{10}(\Delta K)
\]  

(4.4)

This is a straight line equation for mid-range region as shown in figure 4.13 below in log da/dN versus log ΔK. m is the slope of the curve while \(\log_{10}C\) is the y-intercept.

Figure 30: log da/dN against log ΔK in air condition Mild Steel R=0.1

\[
m = \frac{\Delta \log \left(\frac{da}{dN}\right)}{\Delta \log (\Delta K)} = 3.389
\]
C = 10^{-8.9456} = 1.1334 \times 10^{-9}

### Table 2: Calculated values of C and m

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mild Steel</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In 3.5% NaCl</td>
<td></td>
<td></td>
</tr>
<tr>
<td>environment</td>
<td>R= 0.1</td>
<td>1.7968 \times 10^{-9}</td>
</tr>
<tr>
<td></td>
<td>R= 0.5</td>
<td>1.1987 \times 10^{-7}</td>
</tr>
<tr>
<td>In lab air</td>
<td></td>
<td></td>
</tr>
<tr>
<td>conditions</td>
<td>R= 0.1</td>
<td>1.1334 \times 10^{-9}</td>
</tr>
<tr>
<td></td>
<td>R= 0.5</td>
<td>6.6711 \times 10^{-8}</td>
</tr>
<tr>
<td><strong>Aluminium</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In 3.5% NaCl</td>
<td></td>
<td></td>
</tr>
<tr>
<td>environment</td>
<td>R= 0.1</td>
<td>8.838 \times 10^{-9}</td>
</tr>
<tr>
<td></td>
<td>R= 0.5</td>
<td>3.1776 \times 10^{-8}</td>
</tr>
<tr>
<td>In lab air</td>
<td></td>
<td></td>
</tr>
<tr>
<td>conditions</td>
<td>R= 0.1</td>
<td>9.961 \times 10^{-9}</td>
</tr>
<tr>
<td></td>
<td>R= 0.5</td>
<td>5.638 \times 10^{-8}</td>
</tr>
</tbody>
</table>

### 4.4 DISCUSSION

In this experiment we studied the effect of galvanic corrosion on the fatigue crack growth of aluminium and mild steel. Tests are done in air and in sodium chloride environment (3.5% NaCl).

It is worth noting from the graphs that R-ratio has strong effects on the behavior at low growth rates (close to threshold stress intensity factor) from the graphs. From Walker equation [4] the relation between R-ratio and ∆K_{th} is seen to generally agree at lower growth rate than in the intermediate regions.

The graphs of crack length against the number of cycles were drawn. The initial stage showed that the crack appears stagnated. It takes a considerable time before reasonable growth is detected. This was for the first stage of growth where the stress intensity factor was equal or below ∆K_{th}.

In the second stage of the curve, the crack growth was proportional to the number of cycles. The crack grew at a considerable rate which was almost constant. The final stage of the graph showed
higher increase of crack growth rate. The crack length increased with negligible increase of cycles. These graphs of crack length against cycles showed that the life of a material depend on the initial stress intensity factor and environment.

An increase in R-ratio of the cyclic loading causes the growth rates for a given $\Delta K$ to be larger as seen in the graphs for example the graph of mild steel $R= 0.5$ is above the graph $R= 0.1$. It is observed in mild steel that it exhibit weak R effect in the intermediate growth rate of $da/dN$ vs $\Delta K$.

In log $da/dN$ vs log $\Delta K$ C is the intercept while m is the gradient of the line as in fig 4.13. Value of m indicates the degree of sensitivity of the growth rates to stress. The value of m were found to lie between 2-4 agreeing with the theoretical values [4].

From Walker equation the intercept C is a function of R, but the slope m is unaffected by R. in the experiment as shown in the table 4.13 the value of m varied with R. This might have been caused by the machine malfunctioning, the microstructure of the materials and also choosing the best line of fit. It was noted however, that the value of m is affected by change in environment conditions. The value of m in NaCl environment is higher than in lab air conditions. This indicates that the degree of sensitivity of the growth rate to stress is higher in NaCl environment than in lab air conditions.

The value of C was found to increase with increase in R as expected from the Walker equation. The value of C was found to be higher in NaCl environment than in the lab air conditions. This shows that the value of constant C is affected with change in environmental conditions.

The value of C and m in Aluminium do not vary very much with change of the environment and change in R compared to mild steel. This may be partly due to passivity effect.
Fatigue crack growth rate in corrosion medium is observed to be more than in laboratory air conditions as seen in the graphs. The increase in fatigue in corrosion medium may be attributed to embrittlement by chloride ions.

The saturated aggressive chemical environment accelerates crack propagation in addition to the loads acting at the crack tip. Unlike in the plain fatigue testing, the synergistic action involved in the mechanics of corrosion fatigue makes the damage accumulation at faster rates once the crack is initiated. Due to the interaction of saturated chemical solution present at the crack tip with the metal surface, oxide film is produced resulting in the formation of corrosion pits at the metal surface. The corrosion pits are the primary cause further crack initiation. The pits act as notches and produce a reduction in fatigue strength. Usually, this oxide film would act as a protective layer, and prevent further corrosion of the metal. However, cyclic loading causes localized cracking of this layer, which exposes fresh metal surfaces to the corrosive environment. At the same time corrosion causes localized pitting of the surface, and these pits serve as stress concentrations to promote the further damage.

For every increment in crack, fresh material will be subjected to corrosion medium, which results in reduced load required to break the bonds. It is evident that the life of a material is decreased under corrosion medium. The dripping of the liquid near the crack tip ensures reaction with fresh materials.

The corrosion fatigue crack growth rates are more predominant at low stress intensity range compared to growth rate at higher stress intensity range values. At higher stress intensity range, the effect of oxidized induced crack is minimized. It is generally supposed that the crack growth at high values of K is primarily factor of cyclic plasticity [6]. Consequently environmental
conditions should be less significant. This decreasing tendency may be caused by the time
dependence between the actual fatigue action and that of the corrodent-metal surface reaction

Increase in the stress ratio results in a rise of corrosion fatigue crack growth rate. The oxidation
which promotes the crack closure in environmental assisted crack growth is very less as the ear
stress is increased [1]. The effect of corrosion pit formation will be less at higher stress ratios
operation due to the insufficient exposure time at the crack tip. The crack surfaces will not come
into closure sufficiently because of the higher crack mouth opening displacements at crack tip
due to less effect of corrosion pit formation. According to Elber’s crack closure [5], at higher
stress intensity range, the effect of oxidized induced crack is minimized.

Crack closure is due to both the plasticity around the tip and the oxide layer formation at the
crack tip [2]. At higher stress levels, the oxide layer formation will be less, so the plasticity
induced crack closure will dominate. But at lower stress ratios both will show considerable effect
on crack closure.

In Nacl environment, the fatigue crack growth of aluminium is higher than in lab air conditions
as seen in the graphs. The acceleration of fatigue cracks in Al in aqueous solutions originates
probably in embrittlement by chloride ions [7].

Two cracking modes exist in aluminium [6], the tensile mode and the shear mode. Examples
show that the aggressive environment ( NaCl environment) promotes the tensile mode while in a
vaccum the shear mode is predominant. For aluminium alloys normal air has to be considered as
mildly corrosive. A growing fatigue crack usually starts growing in the tensile mode. At free
surface shear lips are formed becoming wider with increasing crack length. If shear lips occupy
the full material thickness crack growth is continued in shear mode. The transition from tensile mode to shear mode depends on the environment, frequency and the temperature.
CHAPTER 5

5.1 CONCLUSIONS

The experiment is a success as we able to show the effect of galvanic corrosion on fatigue crack propagation. We can reduce the effect of corrosion fatigue by the various means discussed in this report but we cannot avoid it hence a fatigue resistance prediction is of the essence.

Fatigue tests in air and corrosion fatigue tests were conducted in a solution of 3.5% NaCl solution were performed on mild steel and aluminium. It was concluded:

1. It is observed that there is an increase in the crack growth rate for the material when tested in 3.5% saturated NaCl environment compared to data obtained under lab air conditions.

2. It is understood that the crack propagation per cycle is very sensitive to stress ratio. At higher stress ratios, the rate by which crack propagates under corrosive environment is less compared to that of crack propagation due to localized crack tip loads.

3. An increase in stress ratio results in a rise in the corrosion fatigue crack growth rate.

5.2 RECOMMENDATIONS

1. Simple superposition models of corrosion fatigue for mild steel and aluminium should be made to predict the effect of corrosion fatigue on these materials.

2. Automation of the fatigue test machine.
6. BIBLIOGRAPHY


7. APPENDIX: 1

Figure 31: Compact tension specimen (CT)
## Appendix: 2

Table 3: Mild Steel R=0.1 calculated values $\Delta K$ and $da/dN$

<table>
<thead>
<tr>
<th>Without corrosion</th>
<th>With corrosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta K$ (MNm$^{1.5}$)</td>
<td>$da/dN$ (mm/cycle)</td>
</tr>
<tr>
<td>10.32039</td>
<td>8.57143E-06</td>
</tr>
<tr>
<td>10.74771</td>
<td>0.000006</td>
</tr>
<tr>
<td>11.37576</td>
<td>5.88235E-06</td>
</tr>
<tr>
<td>11.86952</td>
<td>0.000005</td>
</tr>
<tr>
<td>12.477</td>
<td>7.77778E-06</td>
</tr>
<tr>
<td>13.48046</td>
<td>8.57143E-06</td>
</tr>
<tr>
<td>14.31791</td>
<td>1.07692E-05</td>
</tr>
<tr>
<td>15.51422</td>
<td>0.000014</td>
</tr>
<tr>
<td>16.48592</td>
<td>0.000015</td>
</tr>
<tr>
<td>17.60969</td>
<td>1.77778E-05</td>
</tr>
<tr>
<td>19.94226</td>
<td>3.66667E-05</td>
</tr>
<tr>
<td>22.46883</td>
<td>4.66667E-05</td>
</tr>
<tr>
<td>28.81184</td>
<td>0.000116667</td>
</tr>
<tr>
<td>43.41847</td>
<td>0.00028</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 4: Mild Steel (R=0.5) calculated $\Delta K$ and $\frac{da}{dN}$

<table>
<thead>
<tr>
<th>Without corrosion</th>
<th>With corrosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta K$ (MNm$^{-1.5}$)</td>
<td>$\frac{da}{dN}$ (mm/cycle)</td>
</tr>
<tr>
<td>11.1141</td>
<td>1.14E-05</td>
</tr>
<tr>
<td>11.19168</td>
<td>1.34E-05</td>
</tr>
<tr>
<td>11.38665</td>
<td>1.78E-05</td>
</tr>
<tr>
<td>11.74151</td>
<td>2.00E-05</td>
</tr>
<tr>
<td>12.59256</td>
<td>2.08E-05</td>
</tr>
<tr>
<td>13.1388</td>
<td>2.15E-05</td>
</tr>
<tr>
<td>13.7031</td>
<td>2.20E-05</td>
</tr>
<tr>
<td>14.3802</td>
<td>2.23E-05</td>
</tr>
<tr>
<td>14.8973</td>
<td>2.35E-05</td>
</tr>
<tr>
<td>16.0453</td>
<td>2.70E-05</td>
</tr>
<tr>
<td>16.60447</td>
<td>2.86E-05</td>
</tr>
<tr>
<td>17.448</td>
<td>2.98E-05</td>
</tr>
<tr>
<td>18.2587</td>
<td>3.40E-05</td>
</tr>
<tr>
<td>19.026</td>
<td>3.80E-05</td>
</tr>
<tr>
<td>20.163</td>
<td>4.13E-05</td>
</tr>
<tr>
<td>21.37255</td>
<td>4.82E-05</td>
</tr>
<tr>
<td>22.573</td>
<td>4.96E-05</td>
</tr>
<tr>
<td>24.0335</td>
<td>5.32E-05</td>
</tr>
<tr>
<td>24.9775</td>
<td>5.86E-05</td>
</tr>
<tr>
<td>26.71711</td>
<td>6.66E-05</td>
</tr>
<tr>
<td>29.1501</td>
<td>8.56E-05</td>
</tr>
<tr>
<td>30.30879</td>
<td>1.02E-04</td>
</tr>
<tr>
<td>31.7194</td>
<td>1.23E-04</td>
</tr>
<tr>
<td>32.18829</td>
<td>1.37E-04</td>
</tr>
</tbody>
</table>
### Table 5: Aluminium R=0.1

<table>
<thead>
<tr>
<th>without corrosion</th>
<th>with corrosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta K(mNm^{1.5}))</td>
<td>(\Delta K(mNm^{1.5}))</td>
</tr>
<tr>
<td>5.9003</td>
<td>5.5003</td>
</tr>
<tr>
<td>5.9602</td>
<td>6.07E-06</td>
</tr>
<tr>
<td>6.1113</td>
<td>6.36E-06</td>
</tr>
<tr>
<td>6.2338</td>
<td>6.36E-06</td>
</tr>
<tr>
<td>6.2956</td>
<td>8.34E-06</td>
</tr>
<tr>
<td>6.452</td>
<td>9.54E-06</td>
</tr>
<tr>
<td>6.7081</td>
<td>1.04E-05</td>
</tr>
<tr>
<td>6.9389</td>
<td>1.25E-05</td>
</tr>
<tr>
<td>7.5183</td>
<td>1.34E-05</td>
</tr>
<tr>
<td>7.5303</td>
<td>1.46E-05</td>
</tr>
<tr>
<td>8.1368</td>
<td>2.23E-05</td>
</tr>
<tr>
<td>8.5606</td>
<td>2.54E-05</td>
</tr>
<tr>
<td>9.5037</td>
<td>3.81E-05</td>
</tr>
<tr>
<td>9.8234</td>
<td>4.54E-05</td>
</tr>
<tr>
<td>10.401</td>
<td>4.77E-05</td>
</tr>
<tr>
<td>13.2953</td>
<td>9.71E-05</td>
</tr>
<tr>
<td>15.3178</td>
<td>1.42E-04</td>
</tr>
</tbody>
</table>
Table 6: Aluminium R=0.5

<table>
<thead>
<tr>
<th>Without corrosion</th>
<th>With corrosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔKMN^1.5 da/dN</td>
<td>ΔKMN^1.5 da/dN</td>
</tr>
<tr>
<td>3.9137 2.67E-06</td>
<td>3.852 2.67E-06</td>
</tr>
<tr>
<td>3.9734 4.53E-06</td>
<td>3.9335 4.53E-06</td>
</tr>
<tr>
<td>4.0337 5.24E-06</td>
<td>3.9668 5.24E-06</td>
</tr>
<tr>
<td>4.1013 6.21E-06</td>
<td>4.0203 6.21E-06</td>
</tr>
<tr>
<td>4.2178 6.26E-06</td>
<td>4.1149 7.03E-06</td>
</tr>
<tr>
<td>4.3577 7.03E-06</td>
<td>4.1833 8.71E-06</td>
</tr>
<tr>
<td>4.4433 8.71E-06</td>
<td>4.2664 9.89E-06</td>
</tr>
<tr>
<td>4.8307 9.54E-06</td>
<td>4.3932 1.10E-05</td>
</tr>
<tr>
<td>5.1593 1.21E-05</td>
<td>4.7159 1.34E-05</td>
</tr>
<tr>
<td>5.2942 1.34E-05</td>
<td>5.0283 1.48E-05</td>
</tr>
<tr>
<td>5.6295 1.79E-05</td>
<td>5.2771 1.59E-05</td>
</tr>
<tr>
<td>6.0504 2.38E-05</td>
<td>5.4867 2.08E-05</td>
</tr>
<tr>
<td>6.3688 3.05E-05</td>
<td>5.7544 2.71E-05</td>
</tr>
<tr>
<td>6.8344 4.01E-05</td>
<td>6.0606 3.05E-05</td>
</tr>
<tr>
<td>7.5985 7.03E-05</td>
<td>6.5836 5.27E-05</td>
</tr>
<tr>
<td>8.393  8.34E-05</td>
<td>7.127  7.03E-05</td>
</tr>
<tr>
<td>9.5721 1.29E-04</td>
<td>7.4688 8.34E-05</td>
</tr>
<tr>
<td>10.8207 1.17E-04</td>
<td>8.4626 1.17E-04</td>
</tr>
<tr>
<td>12.1438 1.46E-04</td>
<td>9.0763 1.46E-04</td>
</tr>
<tr>
<td>14.1747 2.30E-04</td>
<td>9.6155 1.81E-04</td>
</tr>
<tr>
<td></td>
<td>10.3092 2.30E-04</td>
</tr>
</tbody>
</table>